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Galactic Cosmic Radiation Doses to Astronauts Outside the Magnetosphere

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Abstract: A review of radiation concerns on manned missions to the Moon, Mars, and other locations outside the magnetosphere is presented.

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GALACTIC COSMIC RADIATION DOSES

TO ASTRONAUTS OUTSIDE THE MAGNETOSPHERE

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ABSTRACT

The dose and dose equivalent from galactic cosmic radiation outside the magnetosphere have been computed. Each of the principal radiation components ~~were~~ considered. ~~These~~ include primary cosmic rays, spallation fragments of the heavy ions, and secondary products (protons, neutrons, alphas, and recoil nuclei) from interactions in tissue. Conventional quality factors were used in converting from dose to dose equivalent.

Three mission environments have been considered: free space, the lunar surface, and the martian surface. The annual dose equivalents to the blood-forming organs in these environments are approximately 500 mSv, 250 mSv, and 120 mSv, respectively (1 mSv = 0.1 rem). The dose on the lunar surface is one-half of free space because there is only a single hemisphere of exposure. The dose on the martian surface is half again the dose on the moon because of the shielding provided by a thin, carbon dioxide atmosphere.

Dose versus aluminum shielding thickness functions have been computed for the free space exposure. Galactic cosmic radiation is energetic and highly penetrating. 30 cm of aluminum shielding reduces the dose equivalent 25% to 40% (depending on the phase of the solar cycle). Aiming for conformity with the draft NCRP annual dose limit for Space Station crew members, which is 500 mSv/yr, we recommend 7.5 cm of aluminum shielding in all habitable areas of spacecraft designed for long-duration missions outside Earth's magnetosphere. This shielding thickness reduces the galactic cosmic ray dose and diminishes the risk to astronauts from energetic particle events. (AU)

THE TRIDENT OF ZEUS

In days of old, Homer chronicled the return of Odysseus and his men from the Trojan War [1]. Disoriented by strong winds, they made land in the country of the Cyclops. They were captured by Polyphemos, son of Poseidon, who began eating them two at a time for dinner. Odysseus devised an escape plan. Polyphemos' eye was put out with a hot, sharpened beam of olive wood. The crew slipped from his cave fastened under ram's bellies. Their ship narrowly escaped being swamped when the blind Cyclops threw great boulders toward it.

Polyphemos cursed his fate and appealed to his father for justice and revenge. Brandishing the trident, Poseidon vexed and harassed Odysseus and his crew for years as they sailed the Ionian Sea. Their journey brought them within a few tens of kilometers of where we meet today [2]. The entire crew was lost and Odysseus alone returned to his home in Ithaca.

Over the ages Poseidon has hounded many sea-faring people, explorers and seamen, as they sought new worlds and earned their living engaged in commerce. Obstacles that were encountered - among them, poor weather, crude navigational equipment, and unreliable winds - have required centuries of scientific and engineering advances to overcome. The risks are now appreciated by all but the foolish and the ignorant.

Today's explorers have advanced into the heavens, the domain of Zeus. They are faced with many threats and risks in the dark, weightless, airless realm of the stars. Among them is space radiation, Zeus' trident: trapped protons and electrons in the Van Allen belts, energetic particles from solar-flare events, and galactic cosmic radiation. Trapped particles are the most intense radiation source; solar energetic particles are the most unpredictable; and galactic cosmic rays are the most pervasive and penetrating.

We look forward here to space missions of the future. As envisioned by the US National Commission on Space [3], the next half century of space exploration and enterprise will offer new and exciting missions not always within reach of Earth's protective skirts. Permanent stations in low-Earth orbit, in geosynchronous orbit, and at the libration points; colonies on the Moon; mining of Phobos and Deimos; and exploratory missions to the surface of Mars are planned. Each of these missions involves a unique and unfamiliar space radiation environment.

Galactic cosmic radiation appears as a prominent risk of manned space travel on these new, long-duration missions. The radiation effects from relatively low-level, long-term exposure to heavy ions in space have not been observed directly. They can be surmised from short-term experimental exposures of animals and the medical histories of human victims. Some of the known risks are leukemia and other cancers, destruction of non-regenerating tissue, cataracts, fetal damage, and genetic mutations. We have used quality factors to account for heavy-ion biological effectiveness with the understanding that this conventional approach may be inadequate.

In this paper we summarize results of calculations of the radiation dose equivalent from cosmic rays on several future space missions outside the magnetosphere. These include missions to the surface of the Moon and Mars, and time spent in unprotected space (either in transit or at a base). For the purpose of shielding studies we report depth versus dose relations in aluminum and lunar soil. We make a special effort to describe the details of our transport calculations, which are extensive. They have required the use of powerful computers (CRAY and VAX) and software developed by many people over the last two decades (HETC, MCNP, UPROP).

METHOD OF CALCULATION

There are three distinct aspects of our calculations. One, the radiation environment in space is modeled. Two, the model radiation environment is transported to the site of radiation damage, for example, at the depth of red bone marrow inside an astronaut in a spacecraft on the surface of the Moon. Three, the radiation dose and dose-equivalent are computed from the arriving particle spectrum using appropriate energy deposition rates and quality factors. Descriptions of each of these parts of the computation follow.

1. Cosmic Radiation Environment

The space radiation environment outside the magnetosphere consists of two prongs of Zeus' trident: galactic cosmic radiation and solar energetic particles. Galactic cosmic radiation consists of nuclei of all elements from hydrogen through uranium moving at relativistic velocities. The flux of cosmic rays is uninterrupted; their intensity varies inversely with solar activity over the 11 year solar cycle. During the solar cycle, galactic cosmic radiation doses change by approximately a factor of two.

Occasional solar flare events inject large numbers of protons into the heliosphere. These particles have somewhat lower average energy than cosmic radiation (about 100 MeV, rather than 1 GeV), but the intensity of energetic particle events easily overwhelms cosmic radiation under typical spacecraft shielding conditions. We will mention briefly the results of calculations involving the August, 1972 flare (the most intense particle event ever observed) and the composite worst-case flare (possibly the worst conceivable particle event).

A radiation environment model including cosmic radiation, solar energetic particles, and other minor radiation components has been devised by the Naval Research Laboratory cosmic ray group and published in a series of reports [4,5,6,7]. The software presented in these publications is called the CREME model. It contains the environmental model, rudimentary transport codes, and microelectronic effects analysis codes. Only the environmental models in this code collection are adequate for radiation dosimetry calculations. The CREME environmental model has been checked against measured particle spectra [8] and found to agree to within (or differ by as much as) a factor of three. Some of the disagreement is probably due to uncertainty in the phase of the solar cycle and limitations of the transport code [9].

2. Transport Models

The physics of heavy-ion transport in materials involves at least three of the fundamental forces (weak, strong, and electromagnetic), a great deal of physical theory developed over the past 50 years, and extensive collections of nuclear data. Modeling of this complex process (Figure 1) can only be approximate. Our computation includes the slowing down of nuclei from electronic interactions in materials (ionization losses), the fragmentation of cosmic ray primaries as they interact in materials and continued transport of the fragments (projectile secondaries), the recoil of heavy target nuclei from proton and neutron collisions (recoil nuclei), and the production of neutrons, protons, and alphas (target secondaries) in inelastic proton collisions.

The passage of heavy cosmic-ray nuclei through shielding materials is modeled using three separate computer codes: UPROP, HETC, and MCNP. Each of these codes is made up of thousands of lines of FORTRAN. Many man-years have been invested in their development. The codes were executed on the DEC VAX 11/785s and the CRAY XMP computer at the Naval Research Laboratory.

UPROP ("Universal Heavy-Ion Propagation Code") transports cosmic-ray primary species and the projectile secondaries. Ionization losses are computed exactly (from a numerical standpoint) over the range from 1 MeV per nucleon to 100 GeV per nucleon using recent theoretical models of ionization loss rates [10]. Fragmentation losses are computed using proton total inelastic cross sections of Letaw et al. [11], nucleus-nucleus total interaction cross sections of Karol [12] modified to correct for skin depth (unpublished), and partial fragmentation cross sections (proton-nucleus and nucleus-nucleus) of Silberberg and Tsao [13, and references therein]. All partial cross sections have been normalized to total inelastic cross sections according to methods outlined by Letaw [14]. (An alternative set of cross sections [15] has not been used in our computations.) Fragmentation and secondary production is recomputed in the target materials at intervals of 0.1 g cm^{-2} (about 0.4 mm aluminum). Some of the data required for these transport computations has been summarized by Letaw et al. [16]; however, the procedures outlined in that paper are directly applicable only to high-energy (> 1 GeV per nucleon) cosmic-ray transport in the galaxy.

HETC ("Monte Carlo High Energy Nucleon-Meson Transport Code") is a well-known code for transporting moderately high-energy protons and neutrons (20 MeV - 3000 MeV) through shielding materials. It does not transport heavy ions, but supplements UPROP by following in detail the production from protons and transport of target

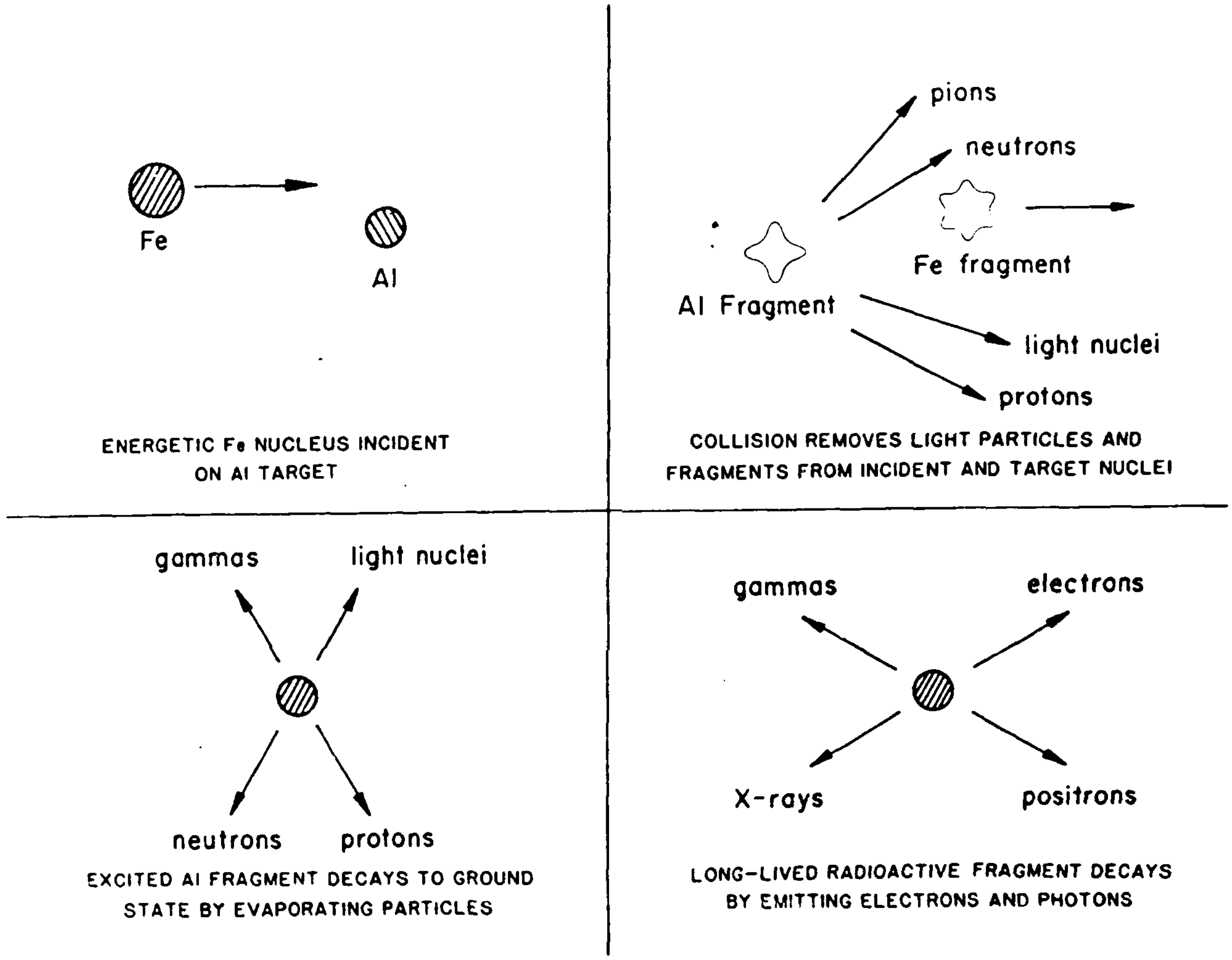

Figure 1. Schematic diagram of secondary particles emitted when a cosmic-ray iron nucleus interacts in aluminum shielding.

secondaries such as protons, neutrons, alpha particles, and pions. It also tabulates the energy and composition of target recoil nuclei and neutrons whose energy falls below a low energy cutoff (20 MeV). HETC was originally developed by Oak Ridge National Laboratory. We have used the Los Alamos National Laboratory (LANL) version of the code [17].

MCNP ("Monte Carlo Neutron and Photon Transport Code") transports relatively low energy neutrons (< 20 MeV) through materials. MCNP also computes the energy deposited (absorbed dose) by secondary neutrons. The LANL version of the code [18] is integrated with both HETC and the Brookhaven National Laboratory's ENDF nuclear database.

3. Conversion to Radiation Dose and Dose Equivalent

The computer codes described above allow the flux of charged particles to be computed at any position in a target (astronaut, spacecraft, planetary atmosphere). In addition, they provide either the energy deposition rate (LET spectrum) or the actual energy deposited by each particle species. These quantities are sufficient to estimate the radiation dose (in gray, Gy) to an astronaut.

The density of energy deposited by charged particles (LET) determines the absorbed radiation dose. For example, an iron nucleus creates a dense core of ionization in any material it passes through. The ionization rate is approximately proportional to Z^2. Thus, iron with Z=26 deposits ionization trails 676 times more dense than protons (Z=1). A number of high-energy iron nuclei deposit a dose in tissue which is 676 times greater than an equal number of minimum ionizing particles at a comparable energy.

The biological effectiveness of various particles for many types of radiation damage is not directly proportional to absorbed dose. Particles with large LET (linear energy transfer) tend to cause long-term radiation effects (such as cancer) much more effectively than minimum ionizing particles. In radiation protection practice, the biological effectiveness of heavy ions is accounted for by multiplying the dose by a quality factor of up to 20 [19]. The resulting quantity, dose equivalent (in sievert, Sv), is 676 x 20 = 13520 times greater for an iron nucleus than for a proton of comparable energy.

The quality factors used in our computations are as follows:

Radiation Component	Adopted QF
Primary heavy ions	1 - 20
Secondary protons	1.2
Secondary deuterons & tritons	1.5
Secondary alphas	3.0
Secondary pions & gammas	1.0
Secondary neutrons	20
Nuclear recoils	20

The quality factor of heavy ions varies as a function of LET as described in Silberberg et al. [20]. The heavy ion quality factor is shown in curve a of Figure 2. Additional explanation of quality factors is presented in Ref. [21]. (Note: We have used a conventional approach to biological effectiveness (quality factors). This approach may require modification as our understanding of long-term, low dose rate exposure to heavy ions increases.)

A new procedure for computing quality factors has been proposed [22]. Figure 2 shows a comparison of the proposed quality factor (curve b) with that used in Ref. [20] (curve a) over a range of energy deposition rates. The minimum LET corresponds roughly to the minimum ionization rate of protons in tissue; the maximum LET corresponds roughly to the maximum ionization rate of iron nuclei in tissue.

The increased quality factor in the middle LET range (corresponding to carbon, oxygen, etc.) slightly dominates the decrease at low and high LET. Overall, the proposed quality factor increases the dose equivalent from galactic cosmic radiation by approximately 35%. The increase would be somewhat greater (50%) if the quality factor for lightly-ionizing protons were bounded below at one.

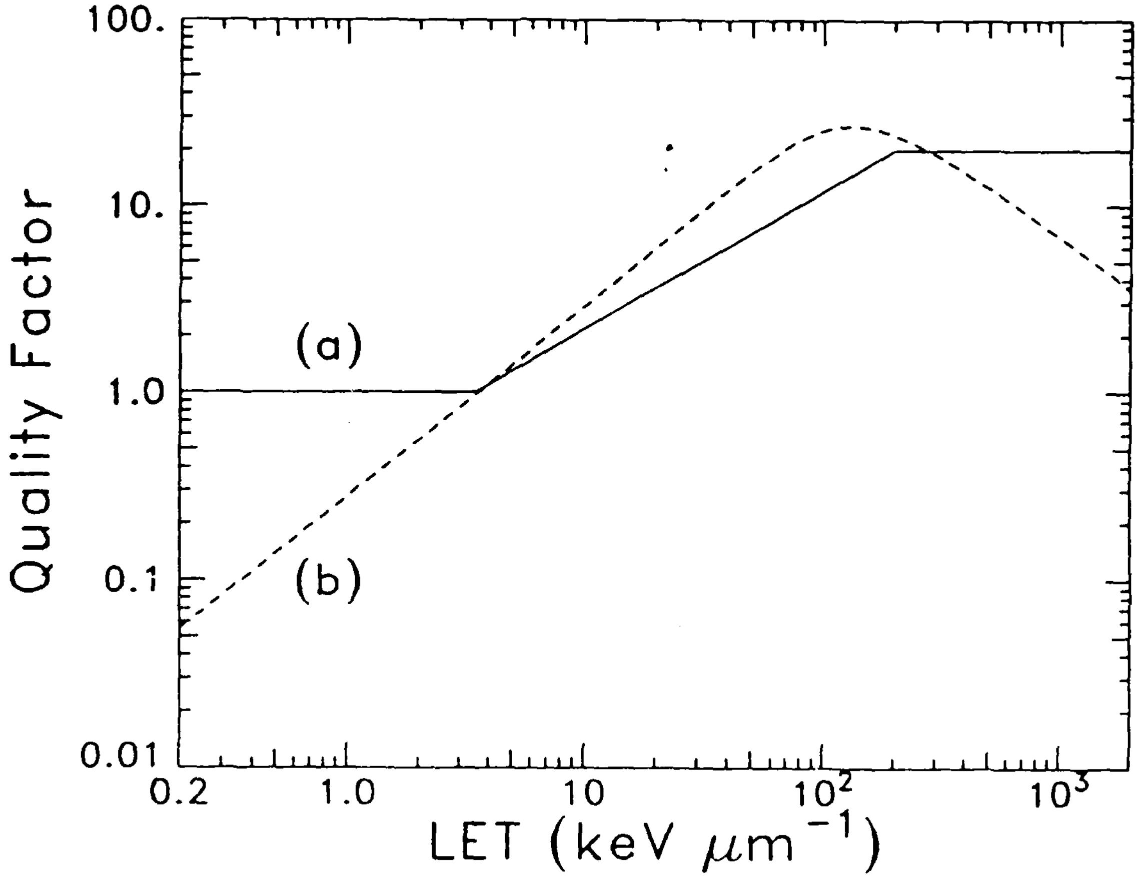

Figure 2. Comparison of heavy-ion quality factors used in this paper (curve a) and proposed by an ICRU/ICRP task group (curve b) as a function of LET in water.

RESULTS

We have considered three different exomagnetospheric galactic cosmic radiation environments. The free space environment is the full intensity of cosmic radiation in the vicinity of Earth. This environment is typical of the exposure of spacecraft in geosynchronous orbit, in transit to the Moon or Mars, or in a station fixed at one of the Lagrange libration points. The lunar surface is shielded from cosmic radiation over one hemisphere by the Moon itself. Mars has a thin atmosphere of carbon dioxide which provides some shielding to astronauts on the martian surface.

Two analyses of the free space environment have been presented [20,21]. The first analysis [20] used a preliminary version of our cosmic radiation transport code (UPROP) to compute primary and projectile secondary fluxes. Other components were estimated using published results. Our estimate of the dose equivalent at the center of a 5 cm sphere of water (corresponding to the tissue shielding of the bone marrow) was 450 mSv yr^{-1}. The second analysis uses a revised version of the CREME environmental model and the secondary components [21] are actually computed using HETC and MCNP. The dose equivalent from primaries and their fragments is increased from 310 mSv yr^{-1} to 440 mSv yr^{-1}. The dose equivalent from the other components is reduced from 140 mSv yr^{-1} to 60 mSv yr^{-1}. The total dose equivalent estimate increases from 450 mSv yr^{-1} to 500 mSv yr^{-1}.

In order to characterize the capacity of aluminum for shielding astronauts from galactic cosmic radiation in free space, dose versus depth curves have been calculated (Figure 3). The heavy ions (primaries and projectile fragments) are attenuated with an e-folding length of about 10 cm. Other secondary components, including neutrons, protons, and heavy recoil nuclei tend to accumulate. With 30 cm (about 1 foot) of aluminum shielding the annual dose equivalent is reduced from 500 mSv to 280 mSv. An identical calculation (Figure 4) performed at solar maximum (cosmic-ray minimum) shows that shielding is much less effective even though the overall dose is lower.

In the free space environment solar energetic particles are a great concern because there is no safe haven. We have made estimates of dose equivalent versus depth in shielding for the August, 1972 flare and the composite worst-case flare (Figure 5). Note that units of that Figure are rem hr^{-1} and that an appropriate flare duration is about 16 hours. About 10 cm of aluminum provides adequate protection for the astronauts (total dose of 400 mSv) in the extremely rare (about once in 20 years) case of a flare comparable to the August, 1972 event. Not even 30 cm of aluminum prevents astronauts from receiving a disabling

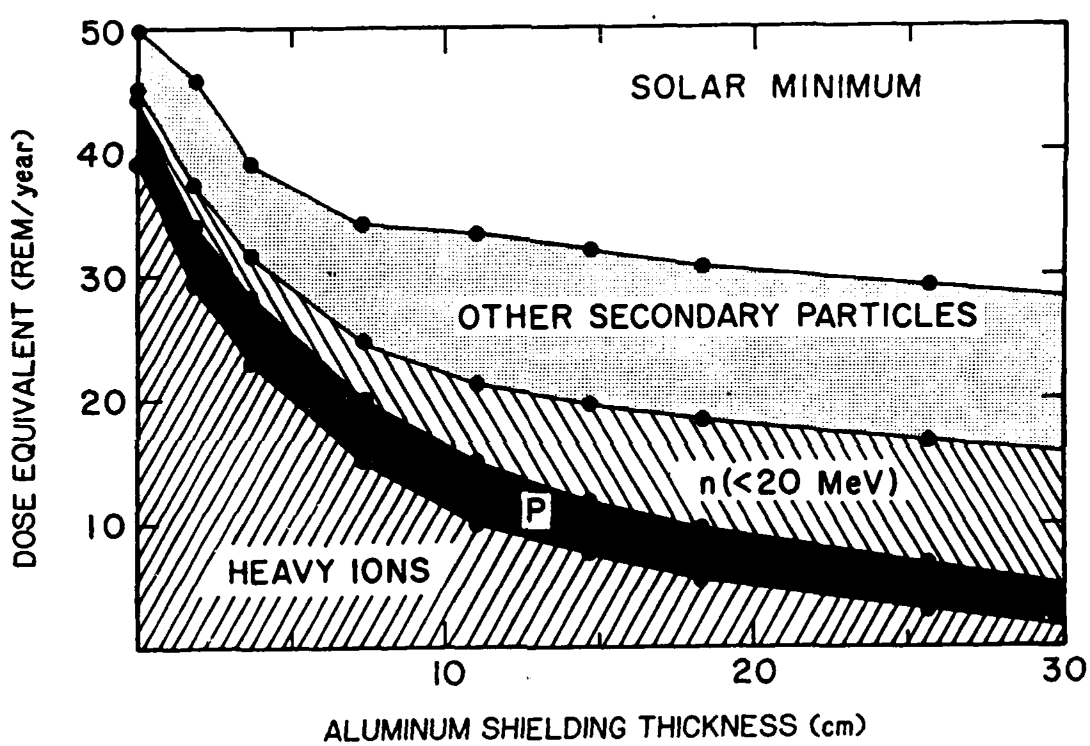

Figure 3. Dose equivalent at 5 cm tissue depth versus aluminum shielding thickness at solar minimum showing radiation components individually.

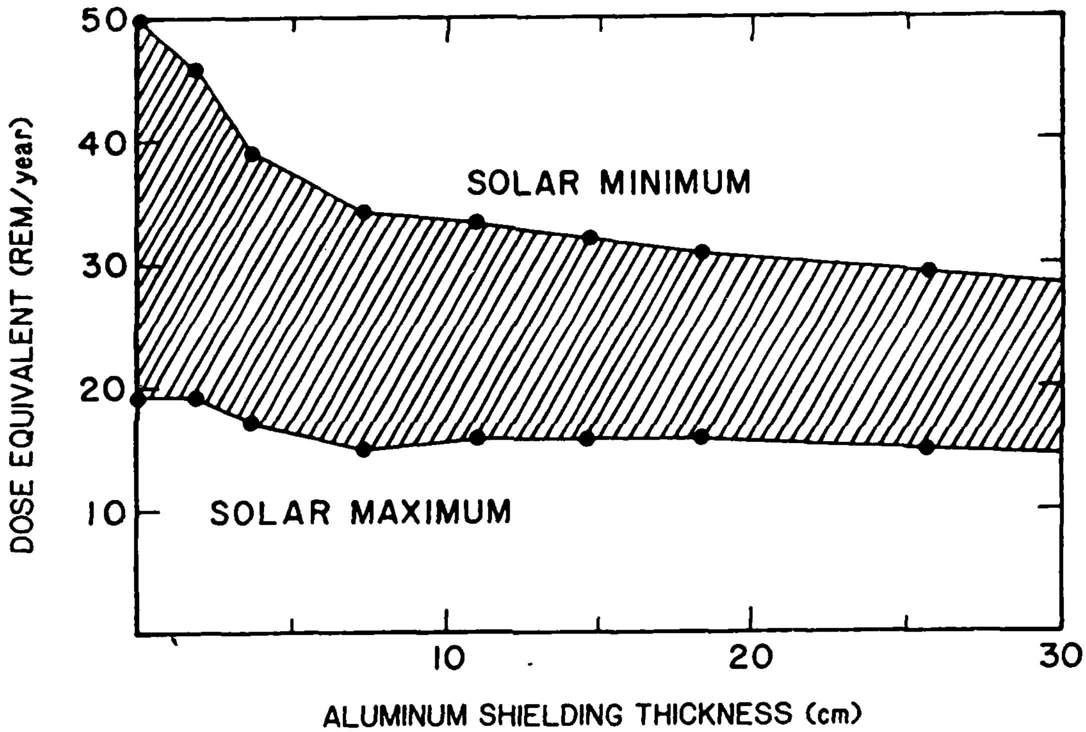

Figure 4. Dose equivalent at 5 cm tissue depth versus aluminum shielding thickness at solar minimum and solar maximum.

dose (above 1000 mSv) from the conceivable, but highly unlikely, worst-case event. Our dose estimates are consistent with, but greater than, other dose estimates [23], because secondary production is considered.

On the surface of the Moon, the annual dose equivalent is about 250 mSv, or one-half of the dose equivalent in free space [24]. The Moon itself shields the astronauts completely over one hemisphere. Under the lunar surface (Figure 6), the build up of secondary particles maintains the annual dose equivalent above 10 mSv yr^{-1} to a depth of 300 cm (about 10 feet).

On the surface of Mars, the annual dose equivalent is about 120 mSv yr^{-1} [25]. The thin, martian atmosphere has about 1% of the pressure of Earth's atmosphere; however, that depth is approximately equivalent to 10 cm of water. The additional shielding reduces the dose equivalent at the martian surface to a factor of two less than on the lunar surface.

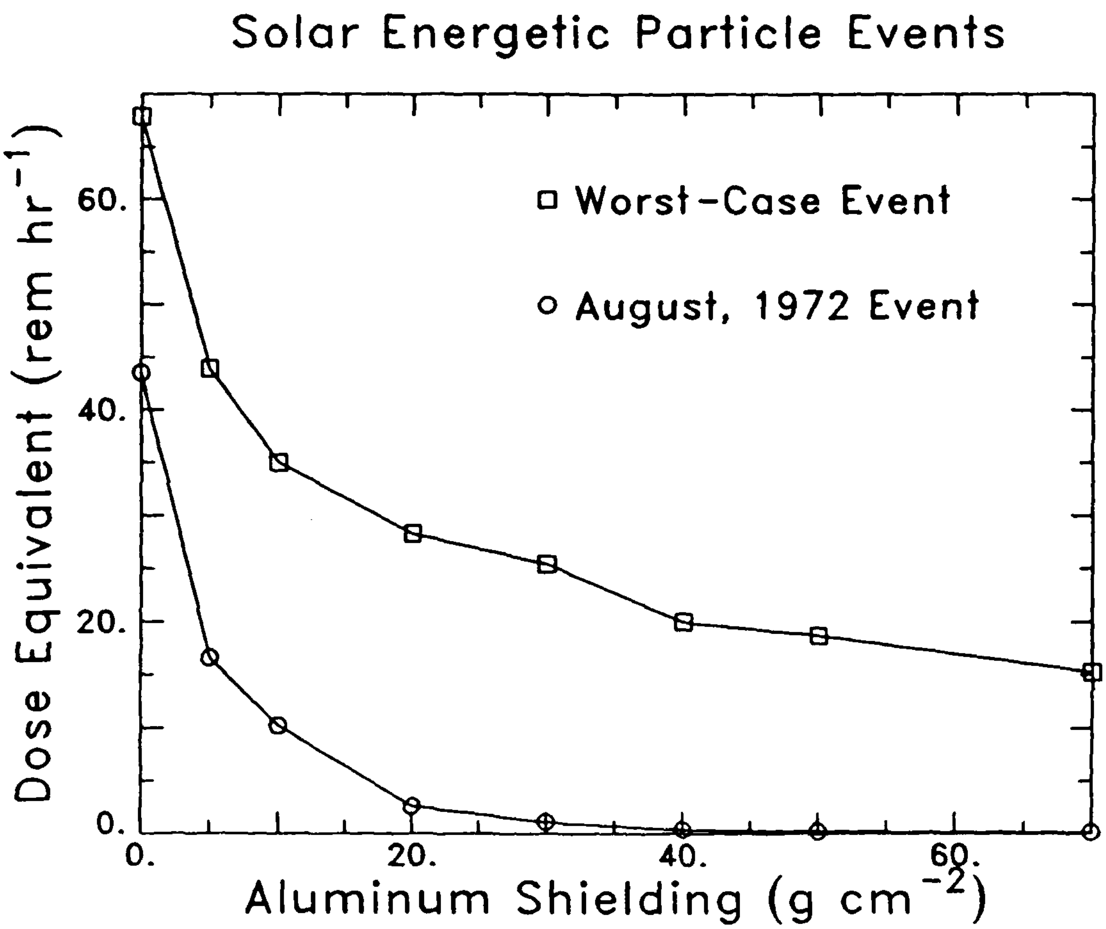

Figure 5. Dose equivalent at 5 cm tissue depth versus aluminum shielding thickness for August, 1972 and composite worst-case solar energetic particle events.

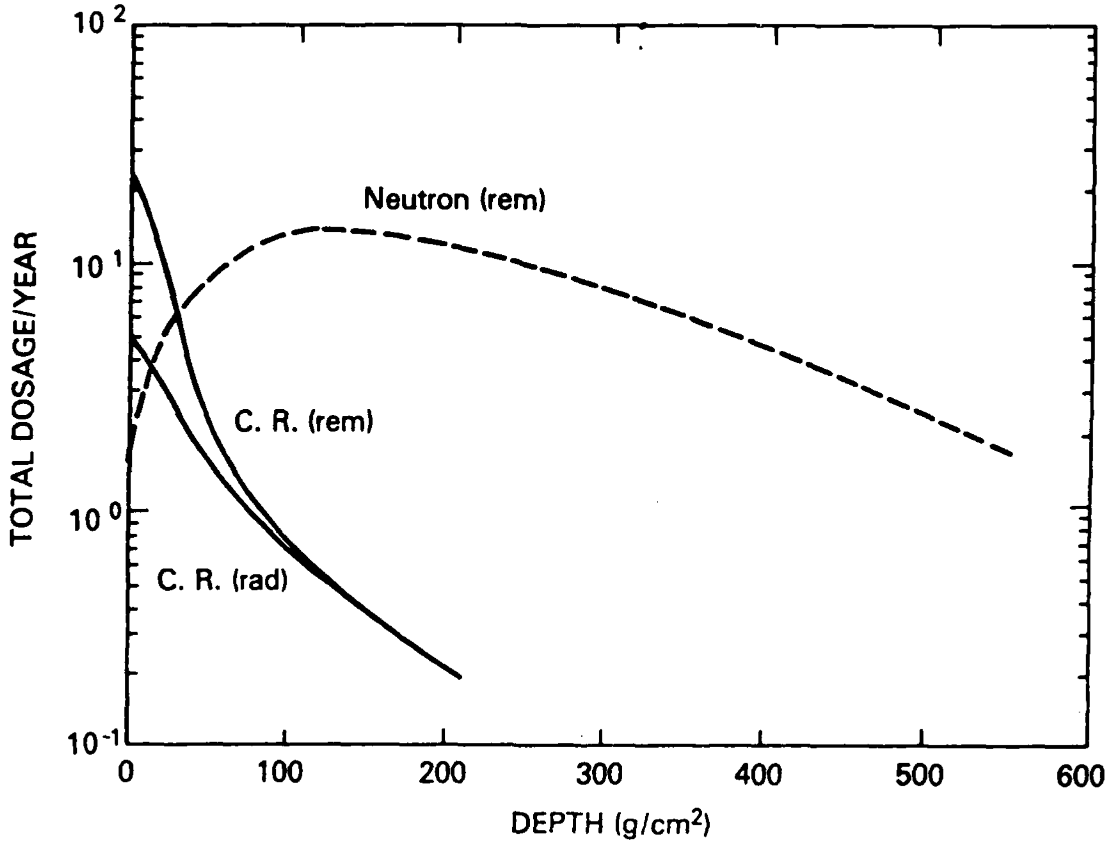

Figure 6. Radiation dose and dose equivalent in lunar soil as a function of depth.

CONCLUSIONS

From the viewpoint of radiation protection, the most hazardous space environment we have discussed is free space, unprotected by magnetic fields, atmospheres, or planetary bodies. Long-term exposure to such a space radiation environment can be expected on the long-duration missions to Mars and its moons, and on space stations in geosynchronous orbit or at the libration points. In this environment astronauts will receive a dose of 200 to 500 mSv yr^{-1} (depending on solar activity) from galactic cosmic radiation. In addition, radiation doses up to, or exceeding, 400 mSv can be anticipated from solar energetic particle events.

About 7.5 cm of aluminum shielding is required in all habitable areas of spacecraft on long-duration missions if we wish to ensure that astronauts receive a dose less than 500 mSv yr^{-1}. The worst-case solar flare dose suggests that there is a potential for all human activity in free space to be interrupted, at infrequent intervals, unless extreme measures are taken to protect astronauts and space workers. We estimate that a worst case flare event occurs no more often than once per century.

Colonies on the surface of the Moon are better protected from space radiation than missions in free space. The surface dose of 250 mSv yr^{-1} is very large by terrestrial standards (we are accustomed, by evolution, to a typical exposure of 1 mSv yr^{-1}). To fall within reasonable limits, say 50 mSv yr^{-1}, colonies must be protected by several meters of lunar soil. To fall within standards for the terrestrial general population (5 mSv yr^{-1}) colonies must be buried under about ten meters of soil and surface excursions must be carefully limited. Even at this depth, a large, reproducing population could be subject to genetic effects.

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